EXHIBIT 2

Water Treatability Database

Per- and Polyfluoroalkyl Substances

Informational Links

Chemicals Dashboard | Analytical Method | EPA Health Advisories | UCMR5

PFAS Explained

Contaminant Navigation

Overview | Treatment Processes | Properties | Fate and Transport | References

Treatment Processes

The following processes were found to be effective for the removal of PFASs: granular activated carbon (GAC) (up to > 99 percent), membrane separation (up to > 99 percent), and ion exchange (up to > 99 percent). Various types of novel adsorptive media have also been found to effectively remove PFASs (up to > 99 percent removal), but results for these media published to date have been limited to bench scale. These results cover the removal of specific PFASs including PFTetA, PFTriA, PFDoA, PFUnA, PFDA, PFNA, PFHpA, PFHxA, PFPeA, PFBA, PFDS, PFNS, PFHpS, PFHxS, PFPeS, PFBS, PFPrS, PFOSA, PFHxSA, PFBSA, 6:2 Cl-PFESA, 8:2 Cl-PFESA, PFMOBA, PFMOPrA, PFMOAA, PFO4DA, PFO3OA, PFO2HxA, FtS 8:2, FtS 6:2, FtS 4:2, 6:6 PFPiA, 6:8 PFPiA, N-EtFOSAA, N-MeFOSAA, ADONA, PFECHS, F35-B, Nafion BP2, GenX, HFPO-TA, and HFPO-TeA. For results on the removal of PFOS and PFOA, see the separate treatability database entries for those specific contaminants.

Studies were identified evaluating the following treatment technologies for the removal of PFASs:

Adsorptive Media

Bench-scale studies tested adsorption of PFASs using novel media including: magnetic nanoparticles with different polymer coatings [2535], functionalized and hybrid hydrogel sorbents [2617, 2606], swellable modified silica with an entrapped cationic polymer [2633], hemp protein powder [2636], modified bentonite [2641], amine-functionalized covalent organic frameworks [2618], cationic covalent organic frameworks [2670] mixed mineral and graphene/carbon-based materials [2622, 2656], zinc-aluminum and magnesium-aluminum layered double hydroxides [2654], zirconium-based metal organic frameworks [2661], amidoxime surface-functionalized electrospun polyacrylonitrile nanofibrous adsorbent [2664], biochar materials [2663, 2669], clay-based adsorbents [2665], cyclodextrin polymers [2638], nonionic resin adsorbents [2677], and two dimensional titanium metal carbides [2677]. One bench-scale study found that amyloid fibril membranes had the capacity to remove certain PFAS, although they generally required low pH levels to achieve high removal efficiency. The study concluded that PFAS removal was due to adsorption (as opposed to size exclusion, which would otherwise categorize the technology as membrane filtration or separation) [2657].

Some of these media achieved moderate to high removals in naturally occurring surface water or groundwater [2636, 2641, 2606, 2622, 2638, 2656, 2657, 2661, 2665, 2669, 2670, 2675]; others were tested only in spiked ultrapure water.

For specific PFASs, results for the best performing of these media include: * Up to 99.9 percent removal of perfluorotetradecanoic acid (PFTetA) * Up to 99.8 percent removal of perfluorotridecanoic acid (PFTriA) * Up to 99 percent removal of perfluorododecanoic acid (PFDoA) * Up to 99.2 percent removal of perfluoroundecanoic acid (PFUnA) * Up to greater than 99 percent removal of perfluorodecanoic acid (PFDA) * Up to greater than 99 percent removal of perfluorononanoic acid (PFNA) * Up to greater than 99 percent removal of perfluoroheptanoic acid (PFHpA) * Up to greater than 99 percent removal of perfluorohexanoic acid (PFHxA) * Up to 97 percent removal of perfluoropentanoic acid (PFPeA) * Up to greater than 99 percent removal of perfluorobutanoic acid (PFBA) * Up to 98.1 percent removal perfluorodecyl sulfonate (PFDS) * Up to greater than 99 percent removal of perfluorononane sulfonate (PFNS) * Up to greater than 99 percent removal of perfluoroheptyl sulfonate (PFHpS) * Up to greater than 99 percent removal of perfluorohexyl sulfonate (PFHxS) * Up to greater than 99 percent removal of perfluoropentanesulfonic acid (PFPeS) * Up to greater than 99 percent removal of perfluorobutyl sulfonate (PFBS) * Up to greater than 99 percent removal of perfluorooctanesulfonamide (PFOSA) * 79 percent removal of perfluorohexanesulfonamide (PFHxSA) * 33 percent removal of perfluorobutylsulfonamide (PFBSA) * Up to 98.9 percent removal 6:2 chlorinated perfluoroether sulfonic acid (6:2 Cl-PFESA) * Up to 98.3 percent removal 8:2 chlorinated perfluoroether sulfonic acid (8:2 Cl-PFESA) * Up to greater than 99 percent removal of fluorotelomer sulfonate 8:2 (FtS 8:2) * Up to 99 percent removal of fluorotelomer sulfonate 6:2 (FtS 6:2) * Up to 87 percent removal of fluorotelomer sulfonate 4:2 (FtS 4:2) * Up to 99.6 percent removal 6:6 perfluorophosphinic acid (6:6 PFPiA) * Up to 99.9 percent removal 6:8 perfluorophosphinic acid (6:8 PFPiA) * Up to 83 percent removal of ammonium 4,8-dioxa-3H-perfluorononanoate (ADONA) * Up to 97 percent removal of perfluoro-4-(perfluoroethyl)cyclohexylsulfonate (PFECHS) * Up to 98 percent removal of F-53B * Up to 99 percent removal of GenX * Up to greater than 99 percent removal of hexafluoropropylene oxide trimer acid (HFPO-TA) * Up to 99.8 percent removal of hexafluoropropylene oxide tetramer acid (HFPO-TeA) * Up to 82 percent removal of 6:2 Fluorotelomer sulfonamidopropyl betaine (6:2 FTAB) * Up to 86 percent removal of 8:2 Fluorotelomer sulfonamidopropyl betaine (8:2 FTAB) * Up to 89 percent removal of 10:2 Fluorotelomer sulfonamidopropyl betaine (10:2 FTAB) * Up to 85 percent removal of 5:1:2 Fluorotelomer betaine (5:1:2 FTB) * Up to 78 percent removal of 7:1:2 Fluorotelomer betaine (7:1:2 FTB) * Up to 81 percent removal of 9:1:2 Fluorotelomer betaine (9:1:2 FTB) * Up to 87 percent removal of 11:1:2 Fluorotelomer betaine (11:1:2 FTB) * Up to 79 percent removal of 5:3 Fluorotelomer betaine (5:3 FTB) * Up to 91 percent removal of 7:3 Fluorotelomer betaine (7:3 FTB) * Up to 86 percent removal of 7:3 Fluorotelomer betaine (9:3 FTB) * Up to 87 percent removal of 11:3 Fluorotelomer betaine (11:3 FTB)

Although results varied depending on the specific media tested, many of these studies show that perfluorinated sulfonates are more readily adsorbed than perfluoroalkyl acids and longer chain PFASs are more readily adsorbed than shorter chain compounds [2535, 2617, 2636, 2641, 2622, 2638, 2654, 2657, 2663, 2670].

See less

At a full-scale site, packed tower aeration was not effective for removing PFASs [2441].

Aeration and Air Stripping See less

Biological Filtration

A full-scale study [2175] of a plant treating reclaimed domestic wastewater found biological filtration to be ineffective for removing per- and polyfluoroalkyl substances.Moderate removal (57 percent) of perfluorodecanoic acid (PFDA) was observed in the biological filtration step at a pilot-scale potable reuse facility, but removal of shorter chain PFAS compounds was much lower (-59 to 25 percent). Removal of perfluorononanoic acid (PFNA) in a full-scale, biologically active carbon filter treating surface water was inconsistent, with some samples showing reductions of PFOS, but others showing increases [2668].

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Biological Treatment

One bench-scale study [2161] examined removal of various PFAS using supernatant from a domestic wastewater activated sludge process as a microbial source in both aerobic and anaerobic test conditions. Although decreases in some of the PFAS tested were observed, concentrations of these PFAS also decreased in the controls. Therefore, the authors concluded that there was no evidence supporting biodegradation for any of the PFAS tested.

See less

Chlorine

Chlorination was ineffective for removing PFASs at full-scale sites [2441, 2619].

See more

Chlorine dioxide was ineffective for removing per- and polyfluoroalkyl substances at a full-scale site [2441].

Chlorine Dioxide See less

Conventional Treatment

Sampling at full scale [2174, 2175, 2441, 2508, 2518, 2619, 2645, 2668] and pilot [2518] drinking water treatment facilities observed either no removal or inconsistent removal of per- and polyfluoroalkyl substances by conventional treatment.

See less

GAC Isotherm

Isotherm data are available for adsorption onto various types of granular activated carbon and onto other media, powdered activated carbon [2637], including anion exchange resin [2426, 2611, 2621, 2637] and novel adsorbents [2522].

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Granular Activated Carbon

Removal of per- and polyfluoroalkyl substances (PFASs) by granular activated carbon (GAC) has been examined in a number of bench and pilot studies and in full scale application. For some of these studies, the primary focus was optimizing the removal of perfluorooctane sulfonate (PFOS) and/or perfluorooctanoic acid (PFOA). Other studies reported on full-scale GAC installations whose objective was treating conventional, as opposed to trace, contaminants. As a result, GAC's performance for the removal of other PFASs was highly variable. In the best cases, however, GAC can be quite effective for many PFAS compounds, with removals of up to greater than 99 percent at bench [2423, 2510, 2511, 2515, 2534, 2561, 2567, 2575, 2626, 2643, 2620, 2638, 2646, 2647, 2663, 2665, 2667], pilot [2559, 2560, 2574, 2616, 2628, 2651, 2652, 2658, 2659], and full-scale [2424, 2441, 2505, 2513, 2564, 2572, 2609, 2616]. Point-of-use GAC devices and pitcher filters are capable of high removals (up to greater than 99 percent) [2430, 2655].

For specific PFASs, results include:

- 90 percent removal of perfluoropropane sulfonate (PFPrS)
- Up to greater than 99 percent removal of perfluorobutanoic acid (PFBA)
- Up to greater than 99 percent removal of perfluorobutyl sulfonate (PFBS)
- Up to 90 percent removal of perfluoropentanoic acid (PFPeA)
- Greater than 99 percent removal of perfluoropentyl sulfonate (PFPeS)
- Up to greater than 99 percent removal of perfluorohexanoic acid (PFHxA)
- Up to greater than 99 percent removal of perfluorohexyl sulfonate (PFHxS)
- Up to greater than 99 percent removal of perfluoroheptanoic acid (PFHpA)
- Up to greater than 99 percent removal of perfluoroheptyl sulfonate (PFHpS)
- Up to greater than 99 percent removal of perfluorononanoic acid (PFNA)
- 96 percent removal of perfluorononane sulfonate (PFNS)
- Up to 99 percent removal of perfluorodecanoic acid (PFDA)
- Up to 90 percent removal of perfluoroundecanoic acid (PFUnA)
- Up to 99 percent removal of perfluorododecanoic acid (PFDoA)
- 90 percent removal of perfluorotridecanoic acid (PFTriA)
- Up to 56 percent removal of perfluorobutylsulfonamide (PFBSA)
- Up to 59 percent removal of perfluorohexanesulfonamide (PFHxSA)
- Up to 95 percent removal of perfluorooctanesulfonamide (PFOSA)
- Up to 70 percent removal of perfluoro-2-methoxyacetic acid (PFMOAA)
- 90 percent removal of perfluoro-3,5-dioxahexanoic acid (PFO2HxA)
- 90 percent removal of perfluoro-3,5,7-trioxaoctanoic acid (PFO3OA)
- 90 percent removal of perfluoro-3,5,7,9-butaoxadecanoic acid (PFO4DA)
- To below detection for fluorotelomer sulfonate 4:2 (FtS 4:2)
- Up to greater than 88 percent removal of fluorotelomer sulfonate 6:2 (FtS 6:2)
- 88 percent removal of fluorotelomer sulfonate 8:2 (FtS 8:2)
- Up to 65 percent removal of perfluoro-4-(perfluoroethyl)cyclohexylsulfonate (PFECHS)
- Up to greater than 99 percent removal of Nafion BP2
- Up to 93 percent removal of GenX

The literature generally shows that perfluorinated sulfonates are more readily adsorbed than perfluoroalkyl acids and longer chain PFASs are more readily adsorbed than shorter chain compounds [2423, 2424, 2515, 2532, 2540, 2577, 2609, 2620, 2626, 2643, 2638, 2663]. The presence of organic matter can have a negative effect on performance, particularly for shorter chain PFASs [2577].

See less

Hydrogen Peroxide See less

Ion Exchange

Removal of per- and polyfluoroalkyl substances (PFASs) using anion exchange resins can be effective. Bench- and pilot-scale studies found removals up to greater than 99 percent [2427, 2503, 2504, 2515, 2523, 2534, 2535, 2538, 2559, 2560, 2563, 2564, 2571, 2576, 2612, 2613, 2616, 2620, 2621, 2627, 2638, 2641, 2643, 2671]. Full-scale applications varied in their results, often depending on whether the treatment process was designed with the objective of removing the specific PFASs measured. The full-scale results showed removals from less than zero to greater than 99 percent [2424, 2441, 2504, 2568]. Among the resins that showed effectiveness were those designed for perchlorate removal, as well as purpose-designed PFAS-selective resins [2504, 2523, 2534, 2538, 2559, 2560, 2564, 2638, 2641, 2643].

For specific PFASs, results include:

- Up to greater than 99 percent removal of perfluorobutanoic acid (PFBA)
- Up to greater than 99 percent removal of perfluorobutyl sulfonate (PFBS)
- Up to greater than 95 percent removal of perfluoropentanoic acid (PFPeA)
- Up to 74 percent removal of perfluoropentyl sulfonate (PFPeS)
- Up to greater than 99 percent removal of perfluorohexyl sulfonate (PFHxS)
- Up to greater than 97 percent removal of perfluorohexanoic acid (PFHxA)
- Up to 99 percent removal of perfluoroheptanoic acid (PFHpA)
- Up to 93 percent removal of perfluoroheptyl sulfonate (PFHpS)
- Up to greater than 99 percent removal of perfluorononanoic acid (PFNA)
- 55 percent removal of perfluorononane sulfonate (PFNS)
- Up to greater than 99 percent removal of perfluorodecanoic acid (PFDA)
- 90 percent removal of perfluoroundecanoic acid (PFUnA)
- Up to greater than 99 percent removal of perfluorododecanoic acid (PFDoA)
- 90 percent removal of perfluorotridecanoic acid (PFTriA)
- 98 percent removal of perfluorobutylsulfonamide (PFBSA)
- 99 percent removal of of perfluorohexanesulfonamide (PFHxSA)
- Up to 98 percent removal of perfluorooctanesulfonamide (PFOSA)
- Greater than 99 percent removal of perfluoro-3-methoxypropanoic acid (PFMOPrA)
- Greater than 99 percent removal of perfluoro-4-methoxybutanoic acid (PFMOBA)
- Up to greater than 99 percent removal of fluorotelomer sulfonate 6:2 (FtS 6:2)
- Up to greater than 99 percent removal for fluorotelomer sulfonate 8:2 (FtS 8:2)
- 97 percent removal of perfluoro-4-(perfluoroethyl)cyclohexylsulfonate (PFECHS)
- Up to greater than 99 percent removal of GenX
- Ineffective (less than 0 percent removal) for 2-(N-Ethyl-perfluorooctanesulfonamido)acetate and 2-(N-Methylperfluorooctanesulfonamido)acetate (N-EtFOSAA and N-MeFOSAA)

The literature also generally shows that ion exchange removes perfluoronated sulfonates more easily than perfluoroalkyl acids and longer chain PFASs more easily than shorter chain compounds [2424, 2515, 2523, 2538, 2540, 2577, 2621, 2627]. The presence of organic matter can have a negative effect on performance, particularly for shorter chain PFASs [2577].

See less

Membrane Filtration

A single bench scale study [2524] observed moderate to high (69 to 84 percent) removal of perfluorohexanoic acid (PFHxA) from spiked lab water by ultrafiltration membranes. Sampling at full scale [2175, 2441] drinking water treatment facilities and a pilot-scale potable reuse facility [2659], however, observed either no removal or inconsistent removal of per- and polyfluoroalkyl substances including PFHxA by ultrafiltration or microfiltration.

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Membrane Separation

Removal of per- and polyfluoroalkyl substances (PFASs) from water using membrane separation was found to be quite effective. Bench [2423, 2514, 2524, 2530, 2547, 2647], pilot [2569, 2571, 2573, 2649, 2651, 2658], and full-scale [2175, 2424, 2428, 2441] studies evaluating several types of nanofiltration (NF) and reverse osmosis (RO) membranes achieved PFAS removals of up to greater than 99 percent. Point-of-use RO devices also obtained high removals [2430, 2567].

For specific PFASs, results include:

- Up to 99.9 percent removal of perfluorobutanoic acid (PFBA)
- Up to 99.8 percent removal of perfluorobutyl sulfonate (PFBS)
- Up to greater than 99 percent removal of perfluoropentanoic acid (PFPeA)
- Greater than 97.5 percent removal of perfluoropentanesulfonic acid (PFPeS)
- Up to greater than 99 percent removal of perfluorohexanoic acid (PFHxA)
- Up to greater than 99 percent removal of perfluorohexyl sulfonate (PFHxS)
- Up to 99 percent removal of perfluoroheptanoic acid (PFHpA)
- Up to 99 percent removal of perfluorononanoic acid (PFNA)
- Up to greater than 99 percent removal of perfluorodecanoic acid (PFDA)
- Up to 99 percent removal of perfluorodecyl sulfonate (PFDS)
- Up to 99 percent removal of perfluoroundecanoic acid (PFUnA)
- Up to greater than 87 percent removal of perfluorododecanoic acid (PFDoA)
- Up to greater than 80 percent removal of perfluoro-3,5-dioxahexanoic acid (PFO2HxA)
- From low influent levels to below limits of quantitation for perfluoro-3,5,7-trioxaoctanoic acid (PFO3OA)
- Up to 98.5 percent removal of perfluorooctanesulfonamide (PFOSA)
- Up to 98.5 percent removal of difluoro(perfluoromethoxy)acetic acid, also known as perfluoro-2-methoxyacetic acid (PFMOAA)
- Up to greater than 99 percent removal of fluorotelomer sulfonate 6:2 (FtS 6:2)
- Up to greater than 83 percent removal and to below limits of quantitation for GenX
- From very low influent levels to below limits of quantitation for 2-(N-Ethyl-perfluorooctanesulfonamido)acetate (N-EtFOSAA)
- Up to greater than 84 percent removal for 2-(N-Methylperfluorooctanesulfonamido)acetate (N-MeFOSAA)

See less

Other Treatment

Other processes that have been evaluated for the treatment of PFASs in groundwater or at environmentally relevant concentrations (e.g., 1 milligram per liter or less) include electrochemical treatment [2630], electrocoagulation [2608], and plasma treatment [2634]. These studies were conducted at the bench scale and did not evaluate the treatment processes for practical use in larger-scale drinking water applications. In one of the groundwaters tested, the electrochemical process [2630] achieved 57 to 89 removal of the PFAS compounds present, which included perfluorobutanoic acid (PFBA), perfluoropentanoic acid (PFPeA), perfluorohexanoic acid (PFHxA), perfluoroheptanoic acid (PFHpA), perfluorobutyl sulfonate (PFBS), perfluorohexyl sulfonate (PFHxS), and perfluoroheptyl sulfonate (PFHpS). In the other groundwater, the process removed 45 to 87 percent of PFHpA, PFBS, and PFHxS. Concentrations of PFBA, PFPeA, PFHxA, however, increased due to the transformation of precursors.

Electrocoagulation [2608] achieved 59 to 87 percent removal of PFBS and 68 to 96 percent removal of PFHxS. Plasma treatment [2634] achieved 70 percent removal or destruction of PFHxS.

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Ozone

Bench- [2647], pilot [2659, 2668], and full-scale studies [2174, 2175, 2441, 2508, 2509, 2518, 2645] found conventional ozonation ineffective for removal of per- and polyfluoroalkyl substances (PFAS). A demonstration study of a patented ozofractionation process, which used ozone gas to separate PFAS into a foam residual, found greater than 98 percent removal of total PFAS, including greater than 82 percent removal of PFPeA, greater than 96 percent removal of PFHxA, and greater than 99 percent removal of 6:2 FtS [2573].

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Ozone and Hydrogen Peroxide

A bench-scale study [2635] using ozone, followed by increasing pH to 11, followed by hydrogen peroxide addition consistently achieved reductions (14 percent to greater than 92 percent) of PFASs including perfluorobutanoic acid (PFBA), perfluoronon...

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Powdered Activated Carbon

Bench [2158, 2521, 2542, 2544] and pilot scale [2518] tests have shown that PAC can be effective for removal of some per- and polyfluoroalkyl substances. Removal depends on factors including PAC dosage, PAC particle size, contact time, and influent water organic carbon. The literature consistently shows that perfluoronated sulfonates are more readily adsorbed than perfluoroalkyl acids and longer chain PFASs are more readily adsorbed than shorter chain compounds. Specific results include:

- Less than 10 percent removal of perfluorobutanoic acid (PFBA)
- Up to greater than 90 percent removal of perfluorobutyl sulfonate (PFBS)
- Up to 40 percent removal of perfluoropentanoic acid (PFPeA)
- Up to 99 percent removal of perfluorohexyl sulfonate (PFHxS)
- Up to greater than 90 percent removal of perfluorohexanoic acid (PFHxA)
- Up to greater than 90 percent removal of perfluoroheptanoic acid (PFHpA)
- Up to 98 percent removal of perfluorononanoic acid (PFNA)
- Up to greater than 90 percent removal of perfluorodecanoic acid (PFDA)

See less

Precipitative Softening See less

Ultraviolet Irradiation

A full-scale study showed ultraviolet irradiation to be ineffective for removing most of the PFASs sampled. Partial removals (32 to 56 percent) were observed in a few samples, however, for perfluorohexylsulfonate (PFHxS) and fluorotelomer sulfonate 6:2 (FtS 6;2) [2441].

- A bench-scale study found that UV degradation of various PFAS compounds can be enhanced (achieving up to 99 percent removal, depending on the specific PFAS) with the addition of sulfite using a contact time of 30 minutes. The study suggested this approach would be promising at scale in groundwater remediation but did not evaluate whether it would be practical for use in drinking water applications [2644].

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Ultraviolet Irradiation and Hydrogen Peroxide

In pilot [2659] and full-scale [2441] studies, advanced oxidation with ultraviolet irradiation and hydrogen peroxide was ineffective for removing any of the PFASs sampled.

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